

Anomalous Couplings at the TeVatron

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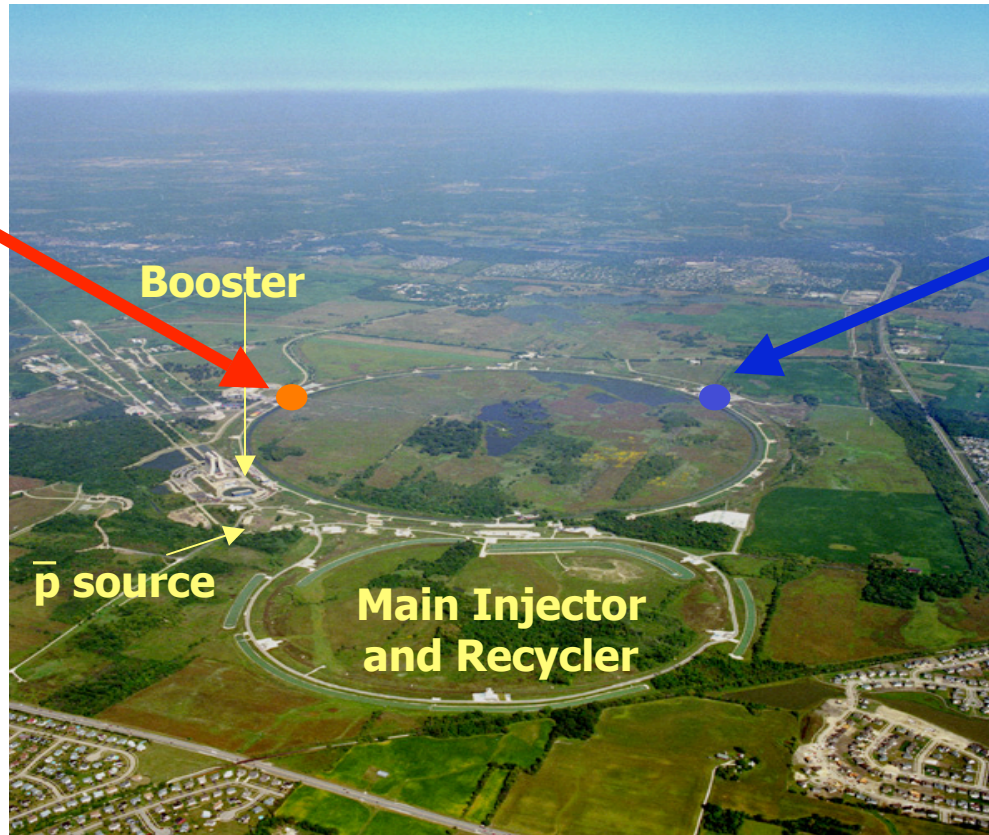
David Waters, University College London

- Introduction
- First Run 2 Results on Di-Boson Production
- Run 2 sensitivity
- Radiation Amplitude Zero
- Conclusions and Questions

The Tevatron: Run 2

CDF

UK institutes:
Glasgow,
Liverpool,
Oxford, UCL



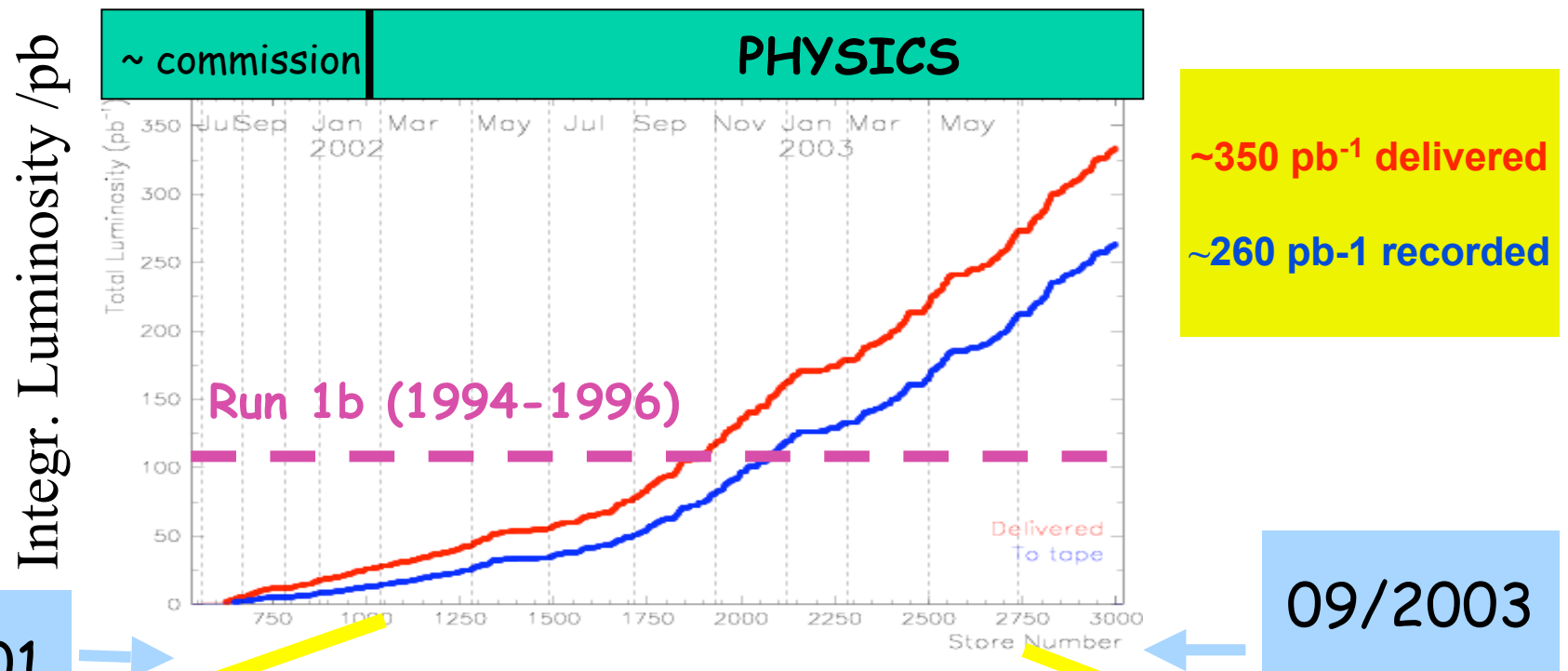
D0

UK institutes:
Imperial,
Lancaster,
Manchester

$p\text{-}\bar{p}$ collisions at $\sqrt{s} \approx 2.0 \text{ TeV}$
bunch crossing rate 396 ns

Bristol, 26/11/2003

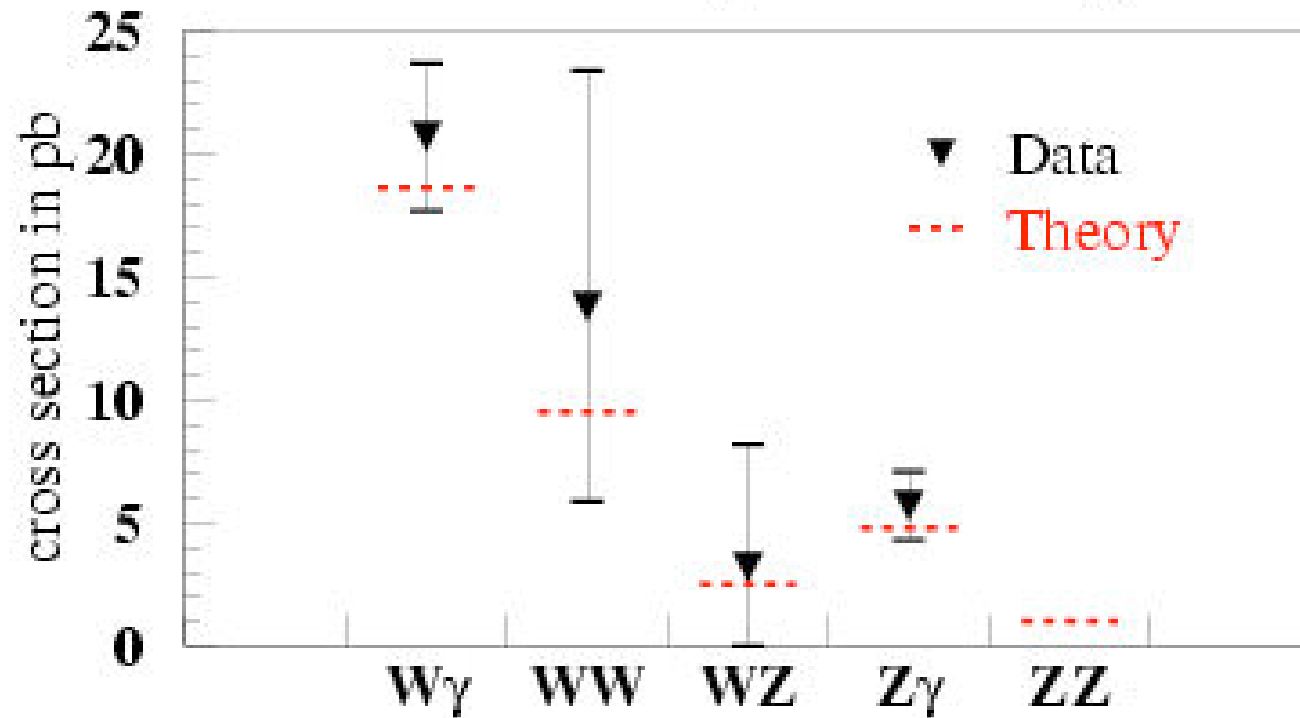
CDF Run 2 Luminosity



Physics Analyses use about 130 pb^{-1} recorded up to June 2003
(about 70 pb^{-1} good quality data on tape up to current shutdown)
Expect 2 /fb by 2006 and 4.4-8.6 /fb by 2009

Di-Boson Production: Run I

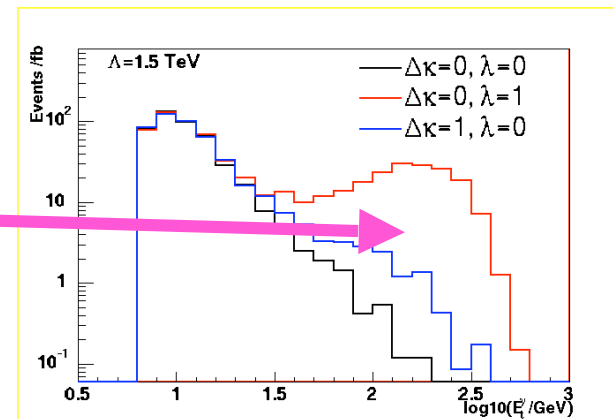
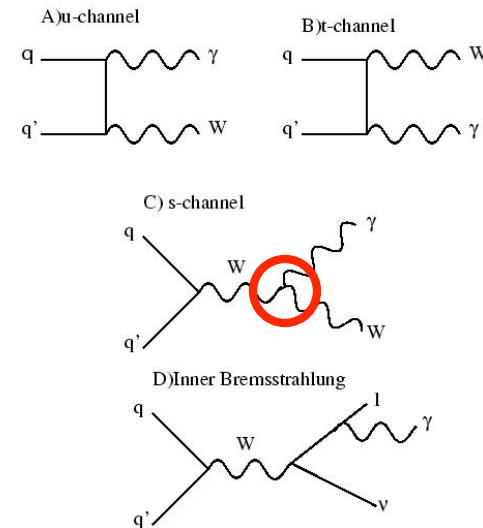
Diboson cross sections from CDF (preliminary)



Di-Bosons: W/Z + Photon

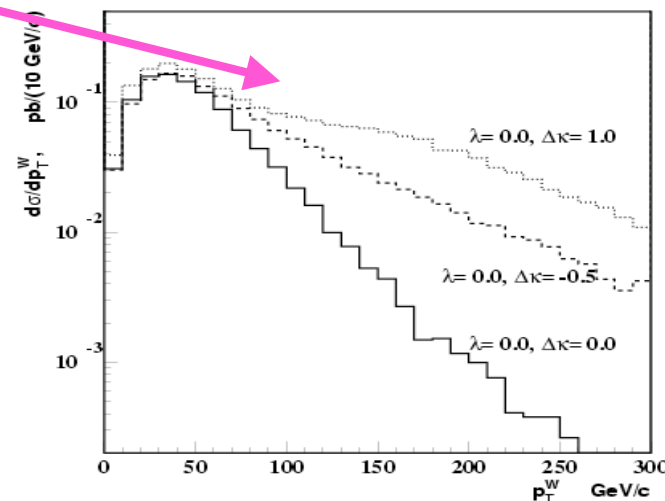
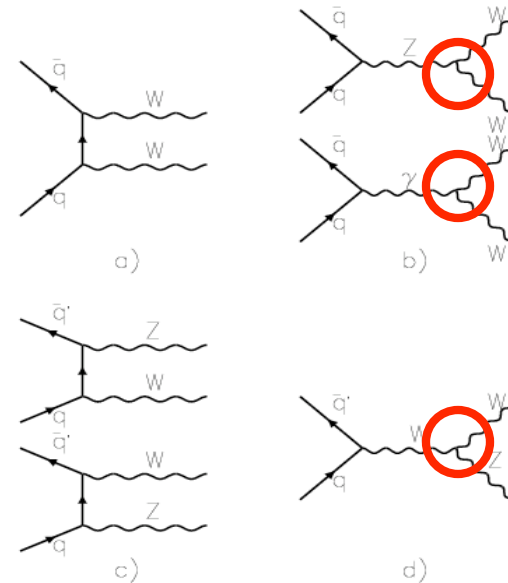
- Construct effective Lagrangian: introduce "anomalous couplings" $\Delta\kappa$ and λ (vanish in SM)
- Cross section rises with s , i.e. violates unitarity \rightarrow introduce form factor Λ :

$$\sigma(s) = \Delta\kappa / [1 + (s/\Lambda^2)]^n$$
- $Z + \gamma$ don't couple to another in SM (diagram C non-existent)
- Non-SM couplings cause harder photon E_T spectrum



Di-Bosons: WW and WZ

- WW production:
 - sensitive to WW_+ and WWZ vertex
 - cross section: $\sigma=13.25$ pb
- WZ production:
 - sensitive to WWZ vertex
 - cross section: $\sigma=2.5$ pb
- Harder W Pt spectrum
- Experimentally two channels:
 - $WW \rightarrow l\nu l\nu$: lepton Pt spectrum sensitive to TGC's
 - $WW/WZ \rightarrow l\nu jj$: jet Et spectrum



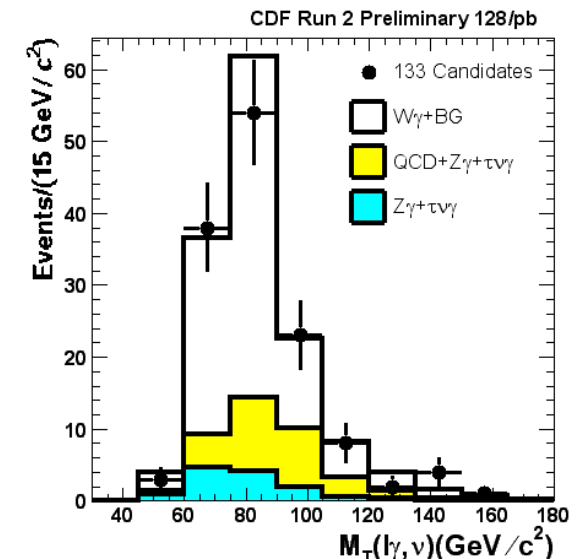
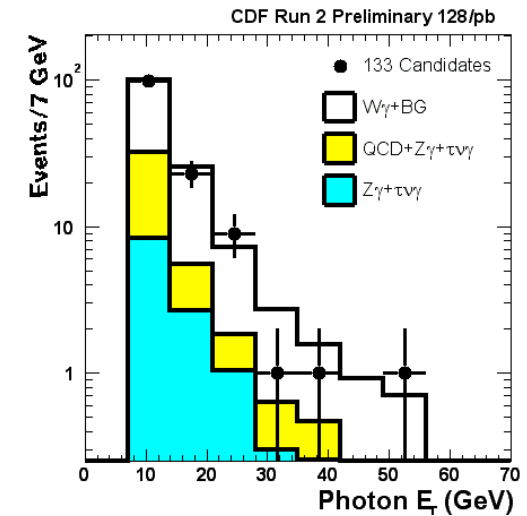
W+ Photon: first Run 2 Results

- Event selection
 - lepton E_t and $M_{et} > 25$ (20) in electron (muon) channel
 - Photon $E_t > 7$ GeV, $_R(l_1) > 0.7$
- Largest uncertainty: BG from jets fragmenting into "single hard π^0 " 30 \pm 10%

	Events
Signal MC	98.9 ± 5.6
Jet \rightarrow _	28.1 ± 9.4
Other BG	13.7 ± 0.7
SM exp.	$140.7 \pm 11.0(\text{sys}) \pm 6.8(\text{lumi})$
Data	133

$$\sigma = 17.2 \pm 2.2(\text{stat.}) \pm 2.0(\text{sys}) \pm 1.1(\text{lumi}) \text{ pb}$$

$$(\text{SM: } \sigma = 18.6 \pm 1.3 \text{ pb})$$



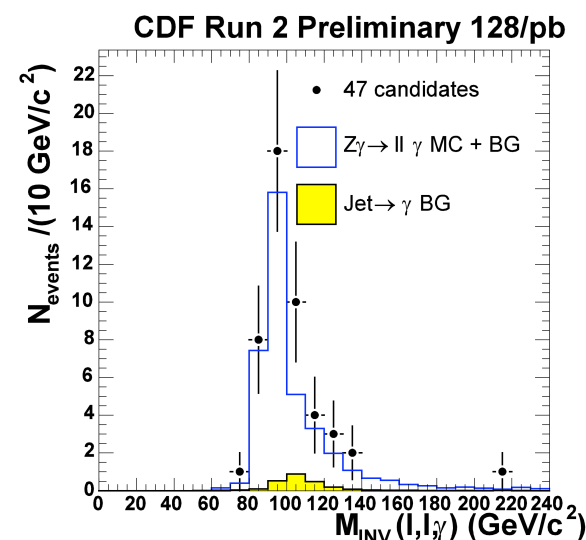
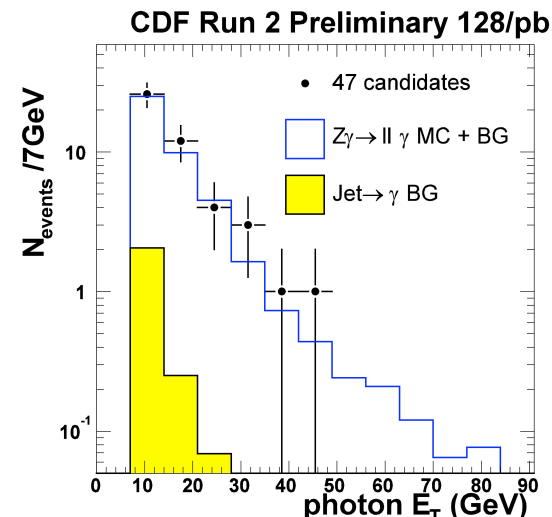
Z+ Photon: first Run 2 Results

- Event selection
 - 2 leptons $E_T > 25$ (20) in electron (muon) channel
 - Photon $E_T > 7$ GeV, $|\eta| > 0.7$
- BG from jets fragmenting into "single hard π^0 " 5%

	Events
Signal MC	40.5 ± 2.3
Jet $\rightarrow \pi^0$	2.5 ± 0.8
Other BG	$0.2 + 0.3 - 0.2$
SM exp.	$43.2 \pm 2.3(\text{sys}) \pm 2.4(\text{lumi})$
Data	47

$$\sigma = 5.8 \pm 0.8(\text{stat.}) \pm 0.3(\text{sys}) \pm 0.4(\text{lumi}) \text{ pb}$$

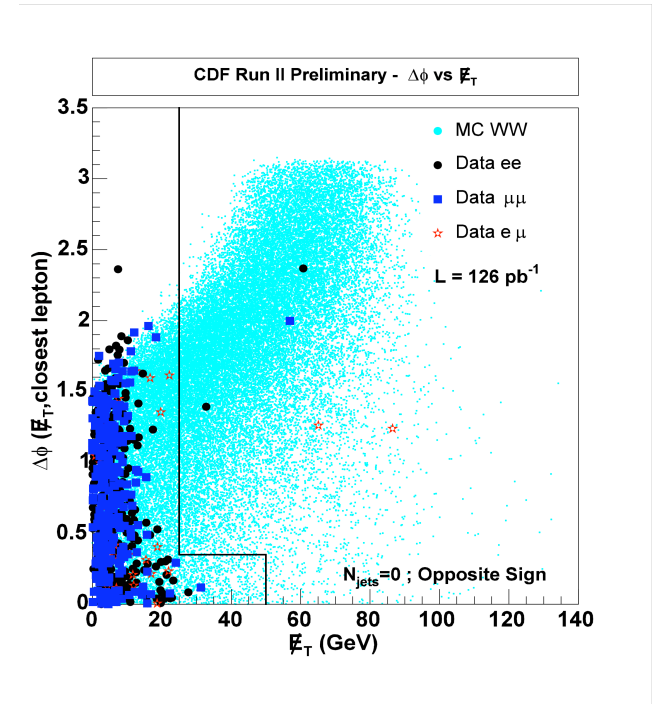
$$(\text{SM: } \sigma = 5.3 \pm 0.4) \text{ pb}$$



WW-Production in Run 2

- both W 's decay leptonically
- Large backgrounds from $t\bar{t} \rightarrow WWbb \rightarrow ll+bb+E_T$
- Suppressed by demanding no jets with $E_T > 10$ GeV
 - Large theoretical uncertainties (LO MC)

	Events
Signal WW MC	6.9 ± 1.5
Drell-Yan	1.4 ± 0.3
Other BG	0.9 ± 0.2
SM exp.	9.2 ± 1.6
Data	5



$$\sigma = 5.1 + 5.4 - 3.6 \pm 1.3 \text{ (sys)} \pm 0.3 \text{ (lumi)} \text{ pb}$$

$$\text{NLO: } 13.25 \pm 0.25 \text{ pb (J.M.Campbell, R.K.Ellis hep-ph/9905386)}$$

Sensitivity to TGC's with 2 fb⁻¹

	$ \Delta\kappa $	$ \lambda $
$W+\gamma$	<0.4	<0.12
WW, WZ_{1jj}	<0.24	<0.16
$WZ_{\text{trileptons}}$	<0.3	<0.2
combined	<0.16	<0.09

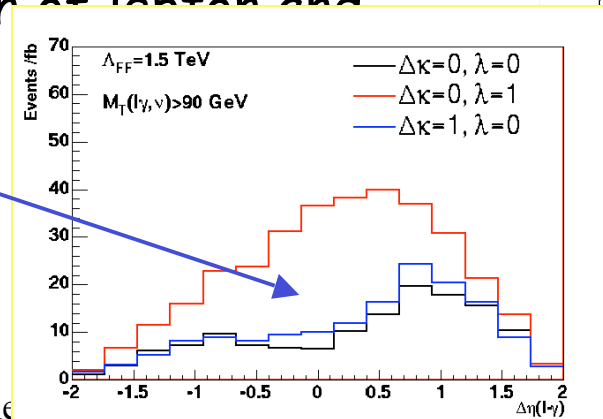
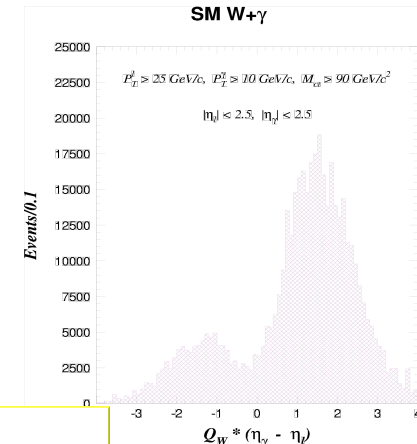
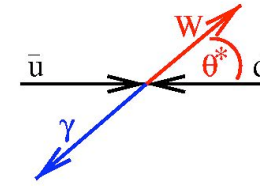
	$ h_{30}(\gamma, Z) $	$ h_{40}(\gamma, Z) $
$Z\gamma_{1^+1^-}$	<0.1	<0.006
$Z\gamma_{\text{_____}}$	<0.04	<0.003

$$\Lambda_{\text{FF}} = 2 \text{ TeV}$$

- Extrapolated from run 1 analyses
- Considered only CP conserving couplings
- Improved detector and analyses techniques should improve sensitivity
- First run 2 publications in 2004
- Main BG to $Z \rightarrow \nu\nu\gamma$ channel are cosmics: new timing in EM calorimeter in CDF will help

Radiation Amplitude Zero

- At LO: exact cancellation of t- and u-channel with s-channel:
 - (W^\pm) suppressed for $\cos^* = (Q_i + Q_j)/Q_W = \pm 1/3$
- "Destroyed" by
 - NLO QCD corrections
 - detector resolution
 - not able to reconstruct \cos^*
- Observable in angular separation of lepton and photon: $Q(l)^*(l - \text{lepton})$
- Anomalous couplings fill in RAZ



TGC and QGC MC generators

- **Anomalous Triple Gauge Couplings:**
 - WGAMMA and ZGAMMA by U. Baur:
 - Can modify TGC's
 - SM cross section checked against CompHep and MadGraph
 - MCFM and BHO for WW, WZ and ZZ
- **Anomalous Quartic Gauge Couplings:**
 - CompHep and MadGraph and WGAMMAGAMMA give SM expectation **but cannot modify QGC's**
 - **No measurements so far** but experimental analysis of 3-boson final states rather trivial extension of di-boson analysis → can measure cross section (or upper limit) now for:
 - $WW_\gamma, ZZ_\gamma, WZ_\gamma$
 - $W_{\gamma\gamma}, Z_{\gamma\gamma}$: "measurable" cross section for $W_{--} (Z_{--})$ about 4 (2) fb (including e and μ channel, both charges, $Pt(<_>) > 10$ GeV, $_{R(1)} > 0.7$, $_{R(<_>)} > 0.3$ (hep-ph/9702364: U. Baur et al.) → **0.8 W_{--} events now, 8 events with 2 fb^{-1} by 2006**

Conclusions

- Tevatron run 2 in progress: expect
 - 2 /fb by 2006
 - 4-8 /fb by 2009
- Have measured $W\gamma$, $Z\gamma$ and WW production cross sections
- Unique possibility to observe RAZ
- UK strongly involved in CDF di-boson analyses
- Will extract and publish TGC's next year
- Can measure tri-boson production cross sections

Questions/Issues

- Is there a QGC MC for pp collisions?
- How shall we treat CP violating couplings?
- Higher sensitivity using multi-dimensional likelihood? E.g. in $W\gamma$: which variable has sensitivity and is uncorrelated with photon E_t ?
- Is sensitivity different for $WW\gamma$ and $W\gamma\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$? What about $WZ\gamma$?
- How interesting is RAZ?
- Form Factor dependence?
- How should we present our results such that they are most useful for theorists/other experiments?